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Structure, Age, and Settings of Formation of Ordovician Complexes of the Northwestern Frame of the Kokchetav Massif, Northern Kazakhstan

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Abstract—This work presents the data on the structure, geochronology, and formation settings of the Ordovician sedimentary and volcanogenic-sedimentary complexes of the Sterlitamak, Mariev, and Imanburluk structural and formational zones located in the western and northwestern frames of the Kokchetav massif (Northern Kazakhstan). In addition, the results of detailed stratigraphic, geochemical, and geochronological studies of the reference section of the Ordovician deposits of the Mariev Zone are given. The studied section is composed of carbonate, terrigenous, and less commonly volcanogenic-sedimentary deposits, confined to a wide stratigraphic interval from Tremadocian Stage of the Lower Ordovician to the lower Sandbian Stage of the Upper Ordovician. For the first time, the study of conodont assemblages made it possible to establish the Early to Middle Ordovician age of the most ancient limestone–dolomite sequence, which was previously conventionally attributed to the Cambrian. The above-lying tuffaceous–terrigenous Kupriyanovka Formation is now attributed to the Middle Ordovician. On the basis of compositional features of the lithoclastic tuffs composing the middle part of the formation, we assume that it was formed within the island arc zone. Limestones from the base of the youngest terrigenous–carbonate Kreshchenovka Formation are attributed to the lower part of the Sandbian Stage of the Upper Ordovician. The study of the geochronology of detrital zircons from terrigenous rocks of the limestone–dolomite sequence has shown that the Early Neoproterozoic quartzite–schist sequences of the Kokchetav massif were the most probable provenance area during its deposition. It was established that there was the change of sedimentation environments from closed lagoons to a relatively deep sea basin with normal salinity and intense circulation of water masses in the northwestern frame of the Kokchetav massif during the Ordovician. During this period of time, there was a sufficiently high level of erosion of provenance areas that resulted in the deposition of thick strata of terrigenous material. A general tendency of the deepening of sedimentation environments from the Early to Late Ordovician was interrupted by sea level rises in the Dapingian and early Darriwilian ages.

Keywords: Northern Kazakhstan, Ordovician, terrigenous–carbonate and tuffaceous–terrigenous strata, biostratigraphy, conodonts, U-Pb dating, detrital zircons

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INTRODUCTION

Ordovician complexes in Northern Kazakhstan are widespread in the western, southern, and eastern frames of the Precambrian Kokchetav massif (Fig. 1). They are represented by siliceous-terrigenous, terrigenous, and volcanogenic-sedimentary formations (Chetverikova, 1960; *Geologiya*..., 1987; Kopyatkevich, 1967; Nikitin, 1972; *Resheniya*..., 1991; Tsai et al., 2001; etc.). A characteristic feature of the Ordovician sequences in the northwestern frame of the massif is occurrence of thick units of carbonate rocks at different stratigraphic levels and small volumes of volcanics (Nikitin, 1963, 1972). The age of these sequences is still insufficiently substantiated owing to a lack of finds of fossil remains and the absence of data on the composition of volcanics, nature of provenance areas, and sedimentation environments. The purpose of this article is to perform paleontological, geochronological, and geochemical studies of Ordovician sedimentary and volcanogenic-sedimentary complexes in the northwestern frame of the Kokchetav massif.

POSITION OF THE ORDOVICIAN SEDIMENTARY AND VOLCANOGENIC-SEDIMENTARY COMPLEXES IN THE WESTERN AND NORTHWESTERN FRAMES OF THE KOKCHETAV MASSIF

The Kokchetav massif, the largest structure in the Caledonides of Northern Kazakhstan, represents an isometric (250 × 200 km) block composed mainly of Late Precambrian metamorphic complexes. The Lower Paleozoic deposits within the massif occur locally and are confined predominantly to the central and eastern parts (Degtyarev et al., 2016). Over 50% of the area of the Kokchetav massif is occupied by large Early to Middle Paleozoic granitoid massifs. Lower Paleozoic complexes are widespread in the frame of the Kokchetav massif, composing several structural and formational zones. To the east and northeast of the massif is the Stepnyak Zone, composed of Ordovician volcanogenic-sedimentary complexes. The southern frame of the massif is outlined by the narrow Chistopol Zone, which is composed of Upper Cambrian siliceous-basalt complexes and Lower–Middle Ordovician siliceous-terrigenous strata, as well as the Kalmykkul Zone, which is composed of Upper Ordovician flysch strata.

The Lower Paleozoic complexes in the western and northwestern frames of the Kokchetav massif are poorly exposed and can be studied only along the banks of the Ishim River and its right tributaries: Imanburluk, Mukyr, and Akkanburluk rivers (Fig. 1). Because of this, there are scarce data on areal extent of many complexes and their relationships. A characteristic feature of the region is wide occurrence of Late Paleozoic and Mesozoic structural transformations, which made Precambrian and Lower Paleozoic complexes significantly complicated.

In the east and northeast of the studied region, the Precambrian formations, an integral part of the basement of the Kokchetav massif, occupy large areas. They are largely composed of weakly metamorphosed Early Neoproterozoic quartzite–schist sequences (Kokchetav Division), while more ancient (Late Mesoproterozoic) rhyolite and basalt-rhyolite complexes (Kuuspek and Imanburluk formations) occupy lower areas (Degtyarev et al., 2015, 2016; *Geologiya*..., 1987; Tretyakov et al., 2011). Structures similar to those in the Kokchetav Division were distinguished within the Efimovka block, which is composed of the eponymous sequence of metaterrigenous rocks (Fig. 1). The Efimovka Formation is composed of frequently alternating sericite–chlorite, carbonaceous, and micaceous-quartz schists containing units of blastopsammitic quartzitic sandstones and rare intercalations of marmorized limestones, folded into large folds. The integrated thickness of the entire sequence is a few hundred meters. Terrigenous rocks contain fragments of kyanite and zircons and, less commonly, tourmaline. Rocks of the Efimovka Formation are intruded by Late Ordovician granitoids of the Baksy pluton. Their relationships with other Precambrian and Paleozoic complexes are tectonic or unexposed. The age of the Efimovka Formation is still unknown. Most likely, it can be attributed to the Late Precambrian, which is evidenced from Nd isotope data obtained for metaterrigenous rocks indicating Neoarchean and Paleoproterozoic ages of provenance areas. According to the structural and compositional features, rocks of the Efimovka Formation are close to those of the Kokchetav Division and can be considered as its facies analog.

Lower Paleozoic complexes, widespread to north and south of the Efimovka block, are substantially different in the structure of sections and the composition of rocks.

To the south of this block, the Lower Paleozoic formations are an integral part of the Sterlitamak Zone, where they were studied in detail along the Ishim and Akkanburluk rivers. Here, there are only Upper Ordovician terrigenous and volcanogenic-sedimentary sequences, which are subdivided into several formations (Chetverikova, 1960; Nikitin, 1972; *Resheniya*..., 1991). Deposits are folded into NE-striking large linear folds, which are accompanied by high-angle longitudinal overthrust faults (Fig. 1). As seen in outcrops, the relationships of Ordovician sequences to more ancient formations are tectonic. In the northern part of the zone, Upper Ordovician volcanics are intruded by granitoids of the Baksy massif and overlapped unconformably by Devonian and Triassic deposits (Fig. 1).

The characteristic feature of terrigenous strata is the sublatitudinal facial variability (Chetverikova, 1960). At the base of the exposed section of the Sterlitamak Zone is flysch deposits of the Andryushino Formation more than 1500 m thick (Fig. 2). The flysch rhythms in the western part of the zone are composed mainly of sandstones and siltstones, less commonly mudstones; in the eastern part are gravellites and conglomerates apart from sandstones and siltstones. Fossil remains in the deposits of the Andryushino Formation are represented only by graptolites attributed to the lower part of the Sandbian Stage of the Upper Ordovician. Higher in the section are fine detrital deposits of the Esil Formation (up to 1000–1500 m), composed of fine-grained sandstones, siltstones, and mudstones with higher carbonate content and thinly laminated bedding (Fig. 2). On the basis of finds of graptolites, the Esil Formation is attributed to the middle part of the Sandbian Stage of the Upper Ordovician. Higher in the succession, this formation is overlain conformably by the terrigenous–carbonate deposits (1500–2000 m) of the Burluk Formation. In the eastern part of the zone, the section of the Burluk Formation is dominated by coarse-grained sandstones and conglomerates; in the western part, by mudstones and siltstones with a subordinate amount of sandstones. Terrigenous deposits in both parts of the zone include intercalations and lenses of organogenic–detrital and organogenic limestones up to 100 m thick. The sequence of this formation contains a very diverse assemblage of brachiopods, trilobites, corals, and graptolites ascribed to the upper Sandbian Stage–lower Katian Stage of the Upper Ordovician. The succession of the Sterlitamak Zone is crowned by the volcanogenic-sedimentary deposits of the Kargaily (Stavropol) Formation up to 2000 m thick, composed mainly of tuffaceous sandstones and tuffaceous conglomerates with flows of intermediate to basic effusives; in the upper part are interbeds of limestones (Fig. 2). In the latter, trilobites and brachiopods of the upper part of the Katian Stage of the Upper Ordovician were found (Nikitin, 1972). As usual, terrigenous deposits of different formations of the Sterlitamak Zone have polymictic composition and are composed of fragments of quartzites, mafic and felsic effusives, sandstones, siltstones, jasper, quartz, and feldspar. A characteristic feature of coarse-grained sandstones and conglomerates from the eastern part of the zone is predominance of red jasper among the clastics; fragments of effusives and sandstones are less common (Chetverikova, 1960).

Structural and compositional features of Ordovician terrigenous and volcanogenic-sedimentary sequences of the Sterlitamak Zone allow us to suggest that they formed in different settings. Accumulation of flysch deposits of the Andryushino Formation and fine terrigenous deposits of the Esil Formation occurred in a large deep basin extending to the east to the Kalmykkul Zone, composed of similar Upper Ordovician terrigenous sequences. The end of the Sandbian time was marked by substantial shallowing of the water basin that is recorded in accumulation of organogenic limestones and coarse-grained rocks. During accumulation of terrigenous sequences, the provenance areas were located in the northeast and east—within the Kokchetav massif and the Chistopol Zone. In the second half of the Katian time, island arc volcanogenic-sedimentary sequences became widespread.

To the north of the Efimovka block is the Mariev Zone, composed of Ordovician deposits which have been the object of our study. They extend in the NNE direction for a distance of 60 km as a zone no more than 6–7 km wide. On this territory, carbonate, terrigenous–carbonate, and terrigenous sequences are widespread. They are folded into submeridional narrow linear folds, which are associated with longitudinal overthrust faults. There are no stratigraphic relationships established between Lower Paleozoic sequences of the Mariev Zone and Precambrian deposits of the Kokchetav massif. At the same time, outcrops of these deposits lie in proximity to each other (lower reaches of the Mukyr River), being separated tectonically (Fig. 1). Therefore, taking into account the composition of complexes of this zone, they can be attributed to cover formations of the Kokchetav massif (see below).

To the northeast of the Mariev Zone is the Imanburluk Zone, which is also composed of Ordovician deposits (Fig. 1). In terms of structure and composition, they are highly different from the coeval deposits of adjacent zones. They have recently been studied in the lower reaches of the Imanburluk River (Degtyarev et al., 2016; Tolmacheva et al., 2016).

Structurally, the complexes of the Imanburluk Zone overthrust the formations of the Mariev Zone, but in most cases there are no contacts exposed. The chert–basalt sequence, occupying the structurally highest position, is considered to be the most ancient in the zone. It composes a thin tectonic sheet, which is underlain by thick olistostrome sequence (Fig. 1). The chert–basalt sequence a few hundred meters thick is composed of aphyric pillow basalt lavas with scarce interbeds of red jasper. In the upper part of the section is a unit of alternating red and green siliceous siltstones, tuffites, cherts and jasper. Thickness of this unit does not exceed 50 m. The conodont assemblage, attributed to the upper Tremadocian Stage of the Lower Ordovician, was extracted from the above rocks (Fig. 2). The composition features of basalts allow us to suggest that formation of the siliceous–basalt sequence occurred in the suprasubduction zone in a back-arc basin with the oceanic crust (Degtyarev et al., 2016).

The olistostrome sequence is overlain by the chert–basalt allochthon and underlain tectonically by carbonate rocks of the Mariev Zone (Fig. 1). The lower part of the zone contains abundant erratic blocks of intermediate and intermediate–basic effusives, surrounding by the matrix made of red nonlaminated siltstones, polymictic sandstones, and small-pebble conglomerates, as well as rare small boulders of red and green siliceous tuffites and cherts. The upper part of the section is dominated by variegated polymictic sandstones, conglomerates, and sedimentary breccias, containing rare boulders and large (up to 100 m) erratic blocks of gray cherts and phtanites, as well as different-sized boulders of gray and pink limestones. Boulders contain different-aged fossil remains: conodonts attributed to the Upper Cambrian and lower and

Fig. 1. Geological scheme of the western frame of the Kokchetav massif. (1) Cenozoic deposits; (2) Middle–Upper Triassic terrigenous sequences, (3) Lower Triassic basalts; (4) Middle Devonian–Permian terrigenous and terrigenous–carbonate sequences; (*5*) Lower Devonian rhyolites and andesites; (6, 7) complexes of the Imanburluk Zone: (6) Upper Ordovician olistostrome strata, (7) Lower Ordovician siliceous-basalt strata; (8–10) complexes of the Mariev Zone: (8) Upper Ordovician Kreshchenovka Formation, (9) Middle Ordovician Kupriyanovka Formation, (10) Lower–Middle Ordovician limestone–dolomite strata; (11–14) Upper Ordovician complexes of the Sterlitamak Zone: (11) Kargaily (Stavropol) Formation, (12) Burluk Formation, (13) Esil Formation, (14) Andryushino Formation; (15) Cambrian ophiolites and siliceous–basalt sequences of the Chistopol Zone; (16) Neoproterozoic quartzite–shale sequences of the Kokchetav massif; (17) Early to Middle Paleozoic granitoids; (18) faults. (I–IV) Early Paleozoic structural and formational zones: (I) Imanburluk, (II) Mariev, (III) Sterlitamak, (IV) Chistopol; (V) Precambrian Efimovka block.

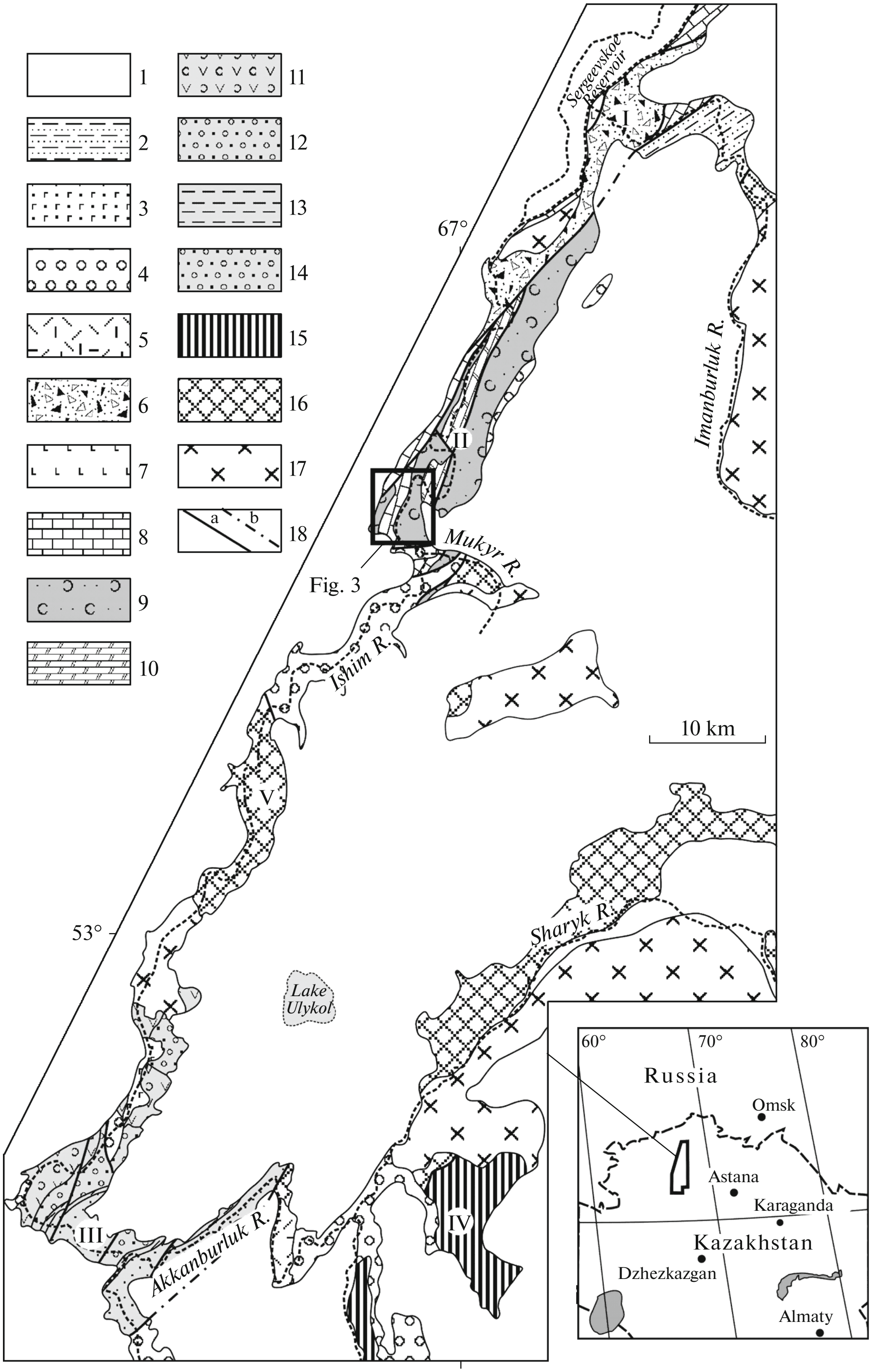
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Fig. 3
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Sharyk R.
Lake Ulykol
Akkanburluk R.
60°
70°
80°
Russia
Omsk
Astana
Karaganda
Kazakhstan
Dzhezkazgan
Almaty

upper parts of the Floian Stage of the Lower Ordovician in cherts; conodonts of the uppermost part of the Floian Stage of the Lower Ordovician, the Dapingian Stage, and the lower part of the Darriwilian Stage of the Middle Ordovician, as well as the upper part of the Middle–Upper Ordovician, in limestones. The age of rocks composing erratic boulders in the olistostrome sequence allows us to suggest that it accumulated at the end of the Late Ordovician (Fig. 2). Rocks composing these boulders are not found in situ within the Kokchetav massif and its western frame. Therefore, it is proposed that formation of olistostrome occurred at the end of Ordovician owing to erosion of the Upper Cambrian–Lower Ordovician siliceous and volcanogenic-sedimentary complexes and the carbonate sequence, covering an age interval from upper Lower to Middle–Upper Ordovician. The latter lies to the northwest of the region studied (Tolmacheva et al., 2016).

In general, complexes of the Mariev Zone compose the thick (up to 5–6 m) tectonic sheet dipping at high angle to the northwest, which is located between Precambrian deposits of the Kokchetav massif and Ordovician complexes of the Imanburluk Zone. The inner structure of this sheet is determined by linear folds predominantly of eastern vergency and complicated by high-angle longitudinal overthrust faults.

STRUCTURE OF SECTIONS AND SUBSTANTIATION OF THE AGE OF SEDIMENTARY AND VOLCANOGENIC-SEDIMENTARY SEQUENCES OF THE MARIEV ZONE

The Ordovician complexes of the Mariev Zone is composed of carbonate, terrigenous, and volcanogenic-sedimentary sequences, which are subdivided from top to bottom into the limestone–dolomite sequence and Kupriyanovka and Kreshchenovka formations (Nikitin, 1963, 1972; *Resheniya*..., 1991). The most complete sections are exposed along both banks of the Ishim River in the area of the settlements of Kupriyanovka and Kreshchenovka (Fig. 3).

The limestone–dolomite sequence lying at the base of the exposed section was distinguished by Nikitin (1963, 1972). The contact of this sequence with more ancient complexes is unknown. The reference section of this sequence was studied in cliffs lined along the left bank of the Ishim River, 3.5 km to the east of the settlement of Kupriyanovka. In addition, some fragments of the sequence were studied on the left bank of the Ishim River to the south of the settlement of Kreshchenovka. The sequence is subdivided into two units, separated tectonically from each other.

Deposits of the upper unit compose a monoclinal structure dipping to the northwest at angles of 60°–80°, broken by longitudinal faults and locally by recumbent folds (Fig. 4). The lower part of this unit is composed of yellow compact dolomites, dolomite breccias, and dolomitic siltstones with intercalations of stromatolitic limestones. To the northwest, yellow compact dolomites, folded into recumbent fold and alternating with brownish red siltstones with intercalations of violet limestones, are exposed. Further to the northwest are monoclinally lying yellow calcareous siltstones and dolomitic breccias, which are followed upsection by siltstones and quartz sandstones. The total thickness of the lower unit is as high as 100–150 m.

The upper unit has a simpler structure; deposits form a monocline structure with high-angle dip (50°–80°) to the northwest. Locally, they are broken by longitudinal overthrust faults, occurring as brecciation zones. The greater part of the upper unit (500–520 m) is composed of monotonous yellowish gray dolomitic siltstones and single beds of reddish dolomitized limestones comprising rare lenticular intercalations of gray pelitomorphic algal limestones varying in thickness from 0.2 to 2 m (Figs. 5c, 5d). On the bedding planes of red dolomitized limestones are ripple marks and mud cracked polygons (Nikitin, 1963). Higher in the section, there are red siltstones, which are followed by yellow calcareous and dolomitic thinly laminated siltstones. The thickness of siltstones is up to 120–130 m; the lower part comprises horizons of fine-grained arenaceous sandstones varying in thickness from 0.5 to 4 m. The limestone–dolomite sequence is crowned by a horizon of dark gray pelitomorphic platy limestones 5 m thick.

The total thickness of the limestone–dolomite sequence exceeds 800 m. It is overlain conformably by black carbonaceous siltstones of the base of the Kupriyanovka Formation.

Conodont elements of the genus *Drepanodus*, not identified to species, were extracted from limestones of the base of the lower unit (Sample Z-1289) and from a thin limestone intercalation lying among dolomitic siltstones at the lower boundary of the upper unit (Sample Z-1273). The conodont elements of the species *Periodon flabellum* were extracted from gray pelitomorphic limestones lying at the upper boundary of the sequence (Sample Z-1275) (Plate I, fig. 6).

According to its position in the sequence, the limestone–dolomite sequence is attributed conventionally to the Cambrian (Nikitin, 1963, 1972; *Resheniya*..., 1991). However, according to new finds of conodonts, the age of sequence can be in an interval from the second half of the Tremadocian Age of the Early Ordovician to the first half of the Dapingian Age of the Middle Ordovician.

The Kupriyanovka tuffaceous–terrigenous formation was distinguished by Nikitin (1963, 1972). It overlies conformably the limestone–dolomite sequence and can be distinguished into three subformations: lower terrigenous, middle tuffaceous, and upper terrigenous.

In general, the lower subformation lies monoclinally with high-angle dipping (50°–75°) to the northwest. The section begins from the unit (about 100 m thick) of alternating black thinly laminated mudstones and siltstones with intercalations and lenses of fine-

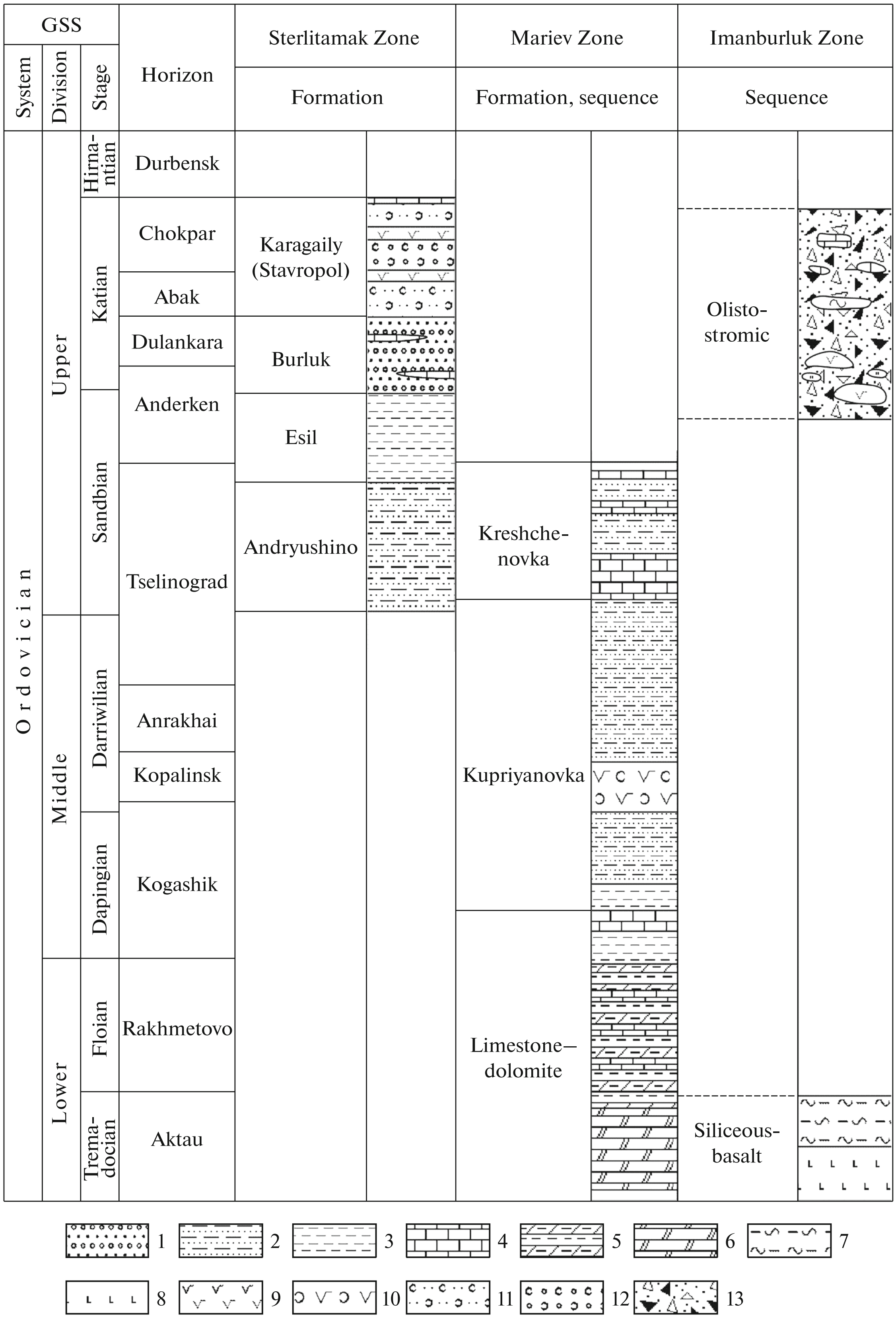


Fig. 2. Correlation scheme of Ordovician sequences from different zones of the western frame of the Kokchetav massif. (1) Alteration of sandstones and conglomerates; (2) alteration of sandstones and siltstones; (3) siltstones and mudstones; (4) limestones; (5) alteration of dolomites and dolomitic siltstones; (6) dolomites; (7) cherts and siliceous siltstones; (8) basalts; (9) andesitobasalts; (10) tuffs of andesitobasalts; (11) olistostrom; (12) tuffoconglomerates; (13) olistostrome. GSS—general stratigraphic scale, Hirn.—Hirnantian.

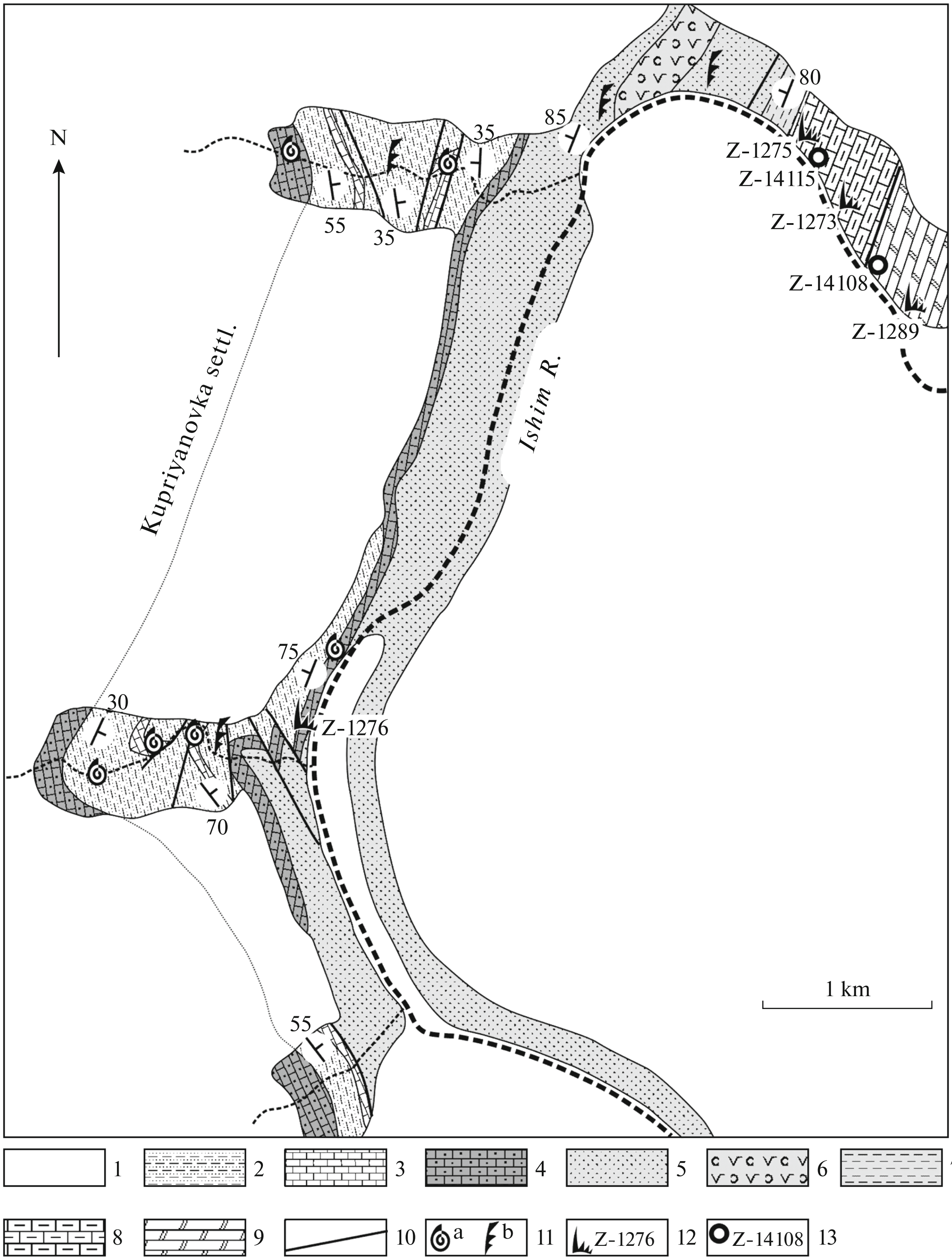


Fig. 3. Geological scheme of the environs of the settlement of Kupriyanovka ((Nikitin, 1972, with amendments)). (1) Cenozoic deposits; (2–4) Upper Ordovician Kreshchenovka Formation: (2) alteration of sandstones and siltstones, (3) horizons and lenses of limestones, (4) reference unit of thinly plated limestones at the base of this section of the formation; (*5–7*) Middle Ordovician Kupriyanovka Formation: (5) sandstones and siltstones, (6) average to mafic lithoclastic tuffs, (7) black siltstones and fine-grained sandstones; (8, 9) Lower–Middle Ordovician limestone–dolomite sequence: (8) upper unit, (9) lower unit; (10) faults; (11) sampling sites of organic remains (Nikitin, 1972): (a) brachiopods and trilobites, (b) graptolites; (12) sampling sites of conodonts and their numbers; (13) sampling sites for geochronological study of detrital zircons and their numbers.

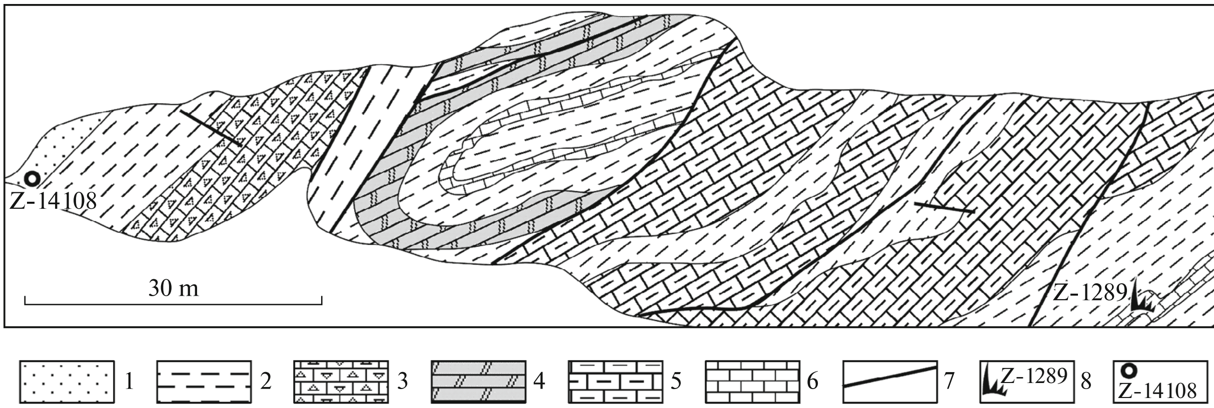


Fig. 4. Geological section of the lower unit of the limestone–dolomite sequence cropping out along the left bank of the Ishim River to the east of the settlement of Kupriyanovka. (1) Sandstones; (2) siltstones; (3) sedimentary breccias made of fragments of dolomites and dolomitic siltstones; (4) dolomites; (5) yellow dolomites and dolomitic siltstones; (6) gray and violet limestones; (7) faults; (8) sampling sites of conodonts and their numbers; (9) sampling sites for geochronological study of detrital zircons and their numbers.

grained sandstones. At the lower boundary of this unit is a continuous horizon of oncolitic limestones 2 m thick, which could be a landslide body lying among the terrigenous deposits. Higher in the section, this unit is followed by the unit of alternating beds (up to 50 cm) of average- to coarse-grained meso- and oligomictic arenaceous sandstones and siltstones, which in turn is followed by siltstones with rare intercalations of fine-grained sandstones. Siltstones and fine-grained sandstones are often red-colored. However, as seen in some cases, such color of rocks is secondary, for variations in color can be recorded within a single bed. The thickness of this part of the section is as high as 150 m, but it is problematic to make an exact estimate (Figs. 5a, 5e). A characteristic feature of this part of the section is the occurrence of several sills of amygdaloidal clinopyroxene basalts up to 1 m thick, folded together with surrounding terrigenous rocks. Higher in the succession, there is the unit of calcareous siltstones with a horizon of dolomitized limestones (15–20 m), which is overlain by dark green siltstones and mudstones (45 m). Th latter is followed by the unit of cross-stratified arenaceous sandstones and siltstones (25 m). The total thickness of the lower subformation is about 350 m.

The middle subformation has a homogenous composition and is composed of coarse lithoclastic tuffs of basic and average to basic composition. Thickness is about 200 m (Fig. 5f). Rock fragments of up to 1.5 m in size composed of porphyry clinopyroxene-plagioclase basalts and amphibole-plagioclase andesitobasalts are cemented by crystalloclastic basic tuffs.

The upper subformation (about 300 m) is composed of greenish gray and green polymictic sandstones and siltstones with thin intercalations and lenses of coarse-grained sandstone. The contact of these rocks with tuffs of the middle subformation is probably tectonic.

The total thickness of the Kupriyanovka Formation is about 800–1000 m. This formation is overlain conformably by limestones of the base of the Kreshchenovka Formation.

Graptolites *Expansograptus* ex. gr. *extensus* (Hall) ascribed to the second half of the Dapingian epoch were extracted from sandstones of the upper part of the lower subformation—graptolites *Glyptograptus dentatus* Brong, *Climatograptus* ex. *Gr. micromacoris* Keller, *Glossograptus* sp., *Corymbograptus* sp. Salter (Early Darriwilian)—from sandstones of the lower part of the upper subformation (Nikitin, 1963, 1972) (Figs. 3 and 6).

The Kupriyanovka Formation was previously attributed to the Lower Ordovician–lower Llanvirnian Stage of the Middle Ordovician (Nikitin, 1963, 1972; *Resheniya*..., 1991). On the basis of new finds of conodonts in the underlying limestone–dolomite sequence, the age of the Kupriyanovka Formation covers an interval from the second half of the Dapingian Age of the Middle Ordovician to the early Sandbian Age of the Late Ordovician. The upper age boundary can be conventionally correlated with the Middle–Upper Ordovician boundary (Fig. 6).

The Kreshchenovka terrigenous–carbonate formation was distinguished by I.F. Nikitin (*Resheniya*..., 1991). This formation was considered previously as one of the reference sections of the Andryushino Formation (Nikitin, 1972).

The Kreshchenovka Formation is composed by gray and greenish gray sandstones and siltstones and gray organogenic limestones with the total thickness of 600–800 m. At the base of the section is a thick (about 50 m) unit of brownish gray massive and platy limestones with intercalations of organogenic-detrital oncolitic rock varieties and calcarenites (Fig. 5b). In the lower part of the carbonate unit, clayey limestones alternate with yellowish gray calcareous siltstones. Limestones contain a large amount of organic remains, including brachiopods, trilobites, and corals.

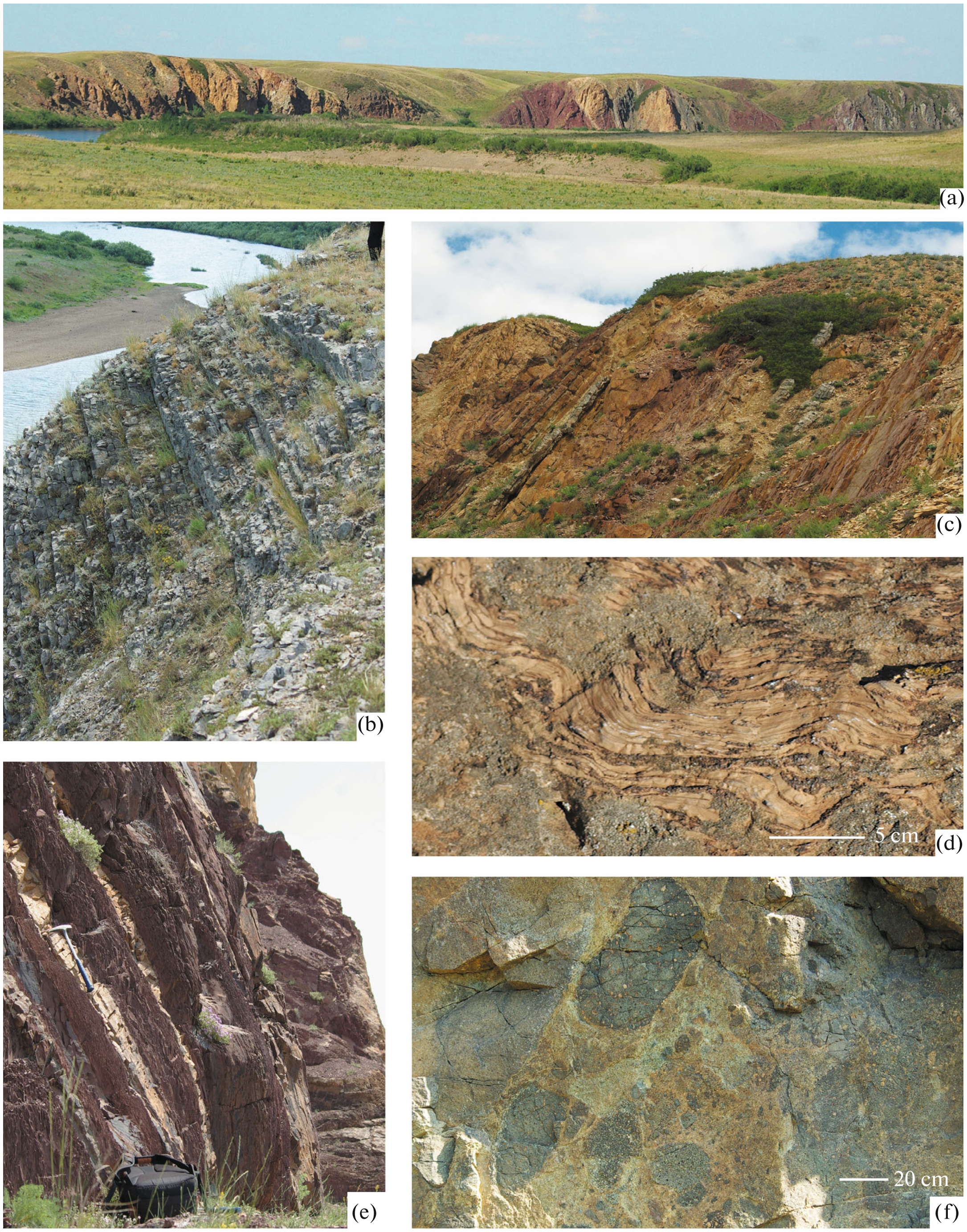
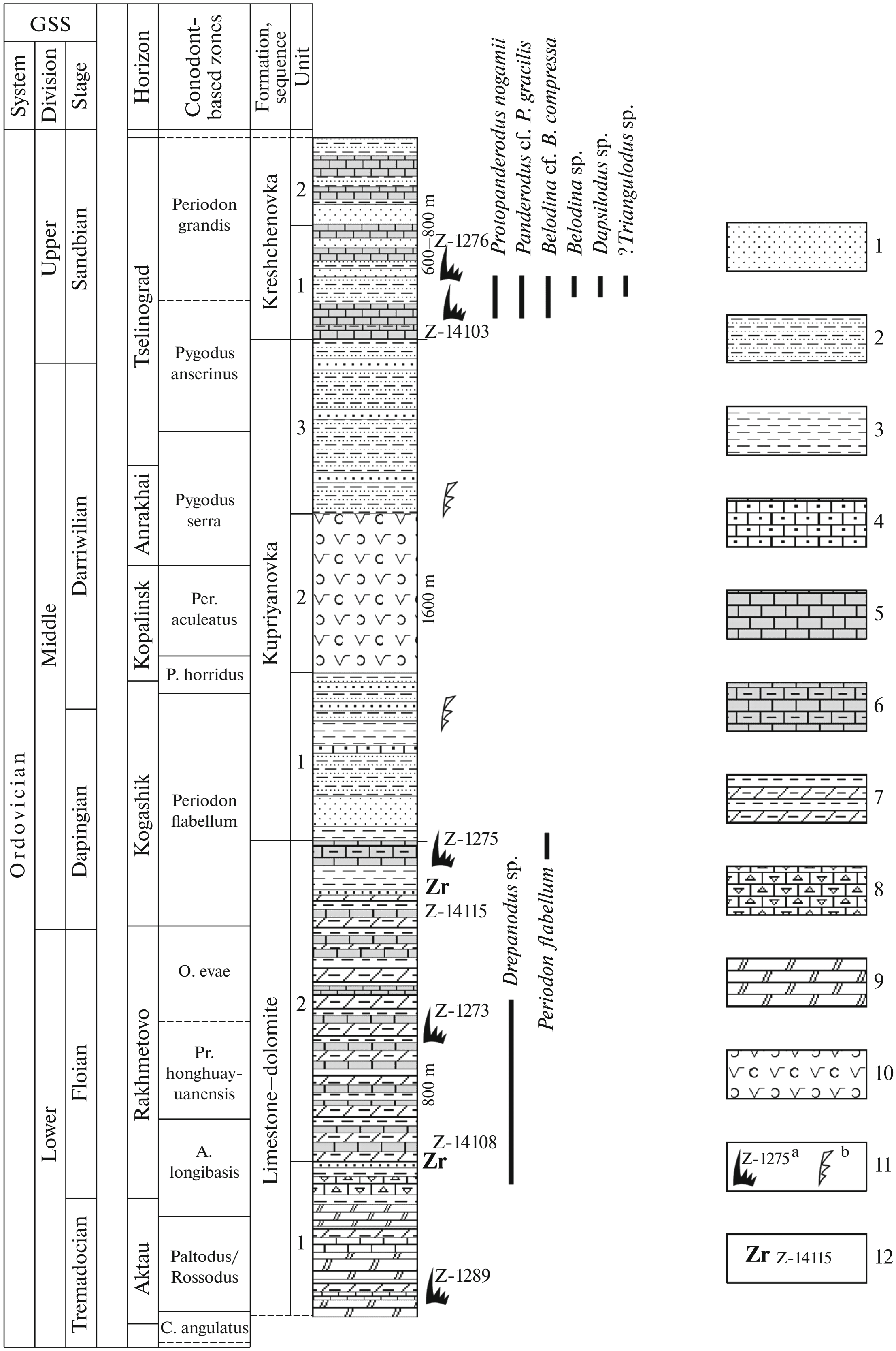


Fig. 5. The character of outcrops and types of rocks from the Ordovician sequences of the Mariev Zone. (a) General view of outcrops of the lower subformation of the Kupriyanovka Formation along the right bank of the Ishim River to the east of the settlement of Kupriyanovka; (b) alternation of thinly laminated limestones in the lower part of the Kreshchenovka Formation; (c) limestone intercalations among dolomitic siltstones and dolomitized limestones in the upper unit of the limestone–dolomite sequence; (d) stromatolitic structures in the upper part of the limestone–dolomite sequence; (e) alternation of sandstones and siltstones in the lower subformation of the Kupriyanovka Formation; (f) lithoclastic tuffs of the middle subformation of the Kupriyanovka Formation.

Fig. 6. Schematic section of the Ordovician sequences of the Mariev Zone cropping out along the left bank of the Ishim River to the east of the settlement of Kupriyanovka, locality sites of studied samples and distribution of conodonts. (1) Sandstones; (2) alteration of sandstones, siltstones, and mudstones; (3) siltstones and mudstones; (4) dolomitic and calcareous siltstones; (5) bioclastic limestones, algal and stromatolitic; (6) pelitomorphic limestones and clayey limestones; (7) alternation of dolomites and dolomitic siltstones; (8) sedimentary breccias with fragments of dolomitic siltstones and dolomites; (9) dolomites; (10) lithoclastic tuffs of mafic and average mafic composition; (11) sampling sites: (a) conodonts and their numbers, (b) graptolites (Nikitin, 1972); (12) sampling sites for geochronological studies of detrital zircons and their numbers. GSS—general stratigraphic scale.


GSS
System
Division
Stage
Horizon
Conodont-based zones
Formation, sequence
Unit
Ordovician
Upper
Middle
Lower
Sandbian
Darriwilian
Dapingian
Floian
Tremadocian
Tselinograd
Anrakhai
Kopalinsk
Kogashik
Rakhmetovo
Aktau
Periodon grandis
Pygodus anserinus
Pygodus serra
Per. aculeatus
P. horridus
Periodon flabellum
O. evae
Pr. honghuay-uanensis
A. longibasis
Paltodus/Rossodus
C. angulatus
Kreshchenovka
Kupriyanovka
Limestone–dolomite
600–800 m
1600 m
800 m
Z-1276
Z-14103
Z-1275
Zr
Z-14115
Z-1273
Z-14108
Zr
Z-1289
Protopanderodus nogamii
Panderodus cf. P. gracilis
Belodina cf. B. compressa
Belodina sp.
Dapsilodus sp.
?Triangulodus sp.
Drepanodus sp.
Periodon flabellum
1
2
3
4
5
6
7
8
9
10
Z-1275 a b
11
Zr Z-14115
12

They are overlain by rhythmically alternating greenish gray polymictic sandstones and green siltstones 40 m thick. Higher in the section, there are gray siltstones and fine-grained sandstones with thick (up to 150 m) units of gray lumpy limestones.

In the early 1960s, brachiopods and single trilobites, determined to genus, were collected in limestones lying at the base of the section of the Kreshchenovka Formation (Nikitin, 1963). Later, brachiopods of subfamilies Strophomenacea and Triplesiacea were identified in this locality (Nikitin and Popov, 1985). This endemic fauna, including *Plectorthis numerosa* Nikitin et Popov, *Titanambonites magnus* Nikitin, *Ishimia ishimensis* Nikitin, *I. radiate* Nikitin, *Shlyginia declivis* Nikitin et Popov, *Sowerbyella verecunda* Nikitin et Popov, *Strophomena digna* Nikitin et Popov, *Macrocoelia platys* Cooper, *Esilia tshetverikovae* Nikitin et Popov, *Triplesia globosa* Nikitin et Popov, was determined and attributed to the Tselinograd horizon of the upper part of the Middle Ordovician–lower part of the Upper Ordovician (Nikitin and Popov, 1985). We identified the following conodonts in these limestones (samples Z-1276, Z-14103): *Panderodus* cf. *P. gracilis*, *Protopanderodus*? *nogamii*, *Belodina* cf. *B. compressa*, *Dapsilodus* sp., *Protopanderodus* sp., ?*Triangulodus* sp., characteristic of the Sandbian Stage of the Upper Ordovician (Plate I, fig. 6).

In the middle part of the section of this formation, an interlayer with brachiopods *Triplesia globosa* Nikitin et Popov, 1985 was identified (Nikitin and Popov, 1985), and in fine-grained sandstones of the uppermost part of the formation, graptolites *Hustedograptus teretiusculus* (Hisinger) and *G. artschalensis* Pavlinov, brachipods *Plectorthis numerosa* Popov, *Lehimia ishimensis* Nikitin, *Titanambonites magnus* Nikitin, and *Esilia tohetvericovae* Nikitin et Popov, and other species attributed to the lower part of the Llandeilian Stage (the upper Darriwilian Stage) were collected (Nikitin, 1963, 1972). At the same time, there were no new finds of organic remains, including conodonts, of good preservation in the middle and upper parts of the section of the Kreshchenovka Formation. Here, limestones are represented mainly by algal and less commonly by crinoid varieties with rare trilobite fragments.

New data on conodonts from limestones of the lower part of the Kreshchenovka Formation indicating its Sandbian (Late Ordovician) age contradict the Llandeilian (Middle Ordovician) volume of the formation, established on the basis of graptolites and brachiopods obtained in the 1960s–1970s and included in the regional stratigraphic scale developed for Kazakhstan (*Resheniya*..., 1991). However, there are no new data on the age of terrigenous and carbonate rocks of the upper part of the formation to correct reliably the age of the Kreshchenovka Formation.

FAUNISTIC CHARACTERISTICS OF ORDOVICIAN COMPLEXES

In general, Ordovician complexes of the northwestern frame of the Kokchetav massif are poorly characterized by finds of organic remains. Shell fossils occur only in Upper Ordovician bioclastic limestones of the Kreshchenovka Formation and are represented by endemic taxa, which make it possible to determine with a great degree of conditionality the age of country deposits (Nikitin, 1974; Nikitin and Popov, 1985; Nikitin et al., 2006). This is a reason why the age of the Kupriyanovka and Kreshchenovka formations was determined previously on the basis of finds of graptolites in terrigenous deposits at several stratigraphic levels (Nikitin, 1963, 1972; Tsai, 1974).

Attempts made to extract conodonts from limestones and dolomites of different sequences show that they occur quite rarely. In total, 12 samples were collected in the previously faunistically undescribed limestone–dolomite sequence, lying at the base of the exposed section. However, only three of them yielded single elements of *Periodon flabellum* and *Drepanodus* sp. (Fig. 6). Bioclastic limestones of the Kreshchenovka Formation yielded 50 conodont elements, among which *Panderodus* cf. *P. gracilis* dominates, and other taxa are represented only by a few elements. All conodonts are well preserved and have low conodont alteration indexes (CAI 2), indicting that thermal heating of deposits did not exceed 150°C.

Finds of conodonts make it possible to determine that the limestone–dolomite sequence attributed previously to the Cambrian covers the age interval from the Lower Ordovician to the lower Middle Ordovician. On the basis of conodonts, the stratigraphic interval of limestones from the lower boundary of the Kreshchenovka Formation, corresponding on the basis of finds of brachiopods to the Tselinograd horizon (the upper

Plate I. Conodonts from carbonates of the limestone–dolomite sequence and the Kreshchenovka Formation. (1, 2, 12) *Protopanderodus? nogamii* (Lee, 1975): (1) S-element, Sample Z-14103, spec. CM 1/11467 (×68); (2) Pa-element, Sample Z-1276, spec. CM 1/11467 (×100), (12) S-element, Sample Z-14103, spec. CM 1/11467 (×57); (3–5, 10, 11) *Panderodus* cf. *P. gracilis*: (3) P-element, Sample Z-14103, spec. CM 1/11467 (×120); (4) P-element, Sample Z-1276, spec. CM 1/11467 (×132); (5) P-element, Sample Z-1276, spec. CM 1/11467 (×97); (10) S-element, Sample Z-1276, spec. CM 1/11467 (×65); (11) S-element, Sample Z-1276, spec. CM 1/11467 (×67); (6) *Belodina* sp., S-element, Sample Z-1276, spec. CM 1/11467 (×45); (7, 8, 9, 13) *Belodina compressa* (Branson et Mehl, 1933): (7) M-element, Sample Z-1276, spec. CM 1/11467 (×76); (8) S-element, Sample Z-1276, spec. CM 1/11467 (×89); (9) S-element, Sample Z-1276, spec. CM 1/11467 (×85); (13) S-element, Sample Z-1276, spec. CM 1/11467 (×56); (14) ?*Triangulodus* sp., M-element, Sample Z-1276, spec. CM 1/11467 (×44); (15, 18) *Periodon flabellum* Lindstrom, 1955: (15) Sb-element, Sample Z-1275, spec. CM 1/11467 (×59); (18) Sc-element, Sample Z-1275, spec. CM 1/11467 (×75); (16) *Drepanodus* sp., S-element, Sample Z-1289, spec. CM 1/11467 (×67); (17) ?*Drepanodus* sp., S-element, Sample Z-1276, spec. CM 1/11467 (×58); (19) *Dapsilodus* sp., S-element, Sample Z-1276, spec. CM 1/11467 (×77).

Plate I

Middle–lower Upper Ordovician), covers only its upper part, which is correlated with the lower part of the Sandbian Stage of the Upper Ordovician.

As we have a poor conodont assemblage, it is possible to evaluate only approximately its paleofacies and paleogeographic characteristics. *Periodon flabellum* and *Drepanodus* sp., identified in limestones from the limestone–dolomite sequence, are typical of pelagic deep-water environments and significantly less common in the shallow facies. The conodont assemblage of the Kreshchenovka Formation with predominance of Panderodus elements and chioline ?*Triangulodus* sp. elements is characteristic of shallow deposits of warm-water seas. In terms of biogeographic confinement, this assemblage is similar to those from other shallow water basins of Kazakhstan, attributed to the Australia–Asian Province (Tolmacheva, 2014).

ANALYTICAL METHODS

The contents of major rock-forming elements were measured using X-ray fluorescence spectroscopy in the laboratory of analytical chemistry at the Geological Institute of the Russian Academy of Sciences, and contents of trace elements were measured at the Institute of Microelectronics Technology Problems and High Purity Materials of the Russian Academy of Sciences using the ICP-MS method (relative error of 5–10%).

The U-Th-Pb geochronological studies of accessory zircons were performed following the standard method using heavy liquids. The morphology of zircon grains was studied using a CAMEBAX SX50 scanning electron microscope in the cathodoluminescence mode.

The U-Th-Pb (ICP-MS) geochronological study of zircons was performed at Macquarie University (Sydney, Australia) on an Agilent 7500s inductively coupled plasma mass spectrometer (ICP-MS) with a New Wave/Merchantek LUV-213 laser microprobe following the method in (Jackson et al., 2004). The crater diameter was 40 μm. Calibration was performed using the Red JG zircon as a calibration standard (Jackson et al., 2004). Zircons Mud Tank (Black and Gulson, 1978; Yuan et al., 2008) and 91500 (Wiedenbeck et al., 1995; Yuan et al., 2008) were used as secondary standards for data quality assessment. As a result, we obtained the following average concordant age values (Ma): Mud Tank = 723.5 ± 4.5 (n = 19), 91500 = 1065.3 ± 17.1 (n = 20), and Red JG = 600.5 ± 3.7 (n = 75), which are well correlated with U-Pb (ID-TIMS) age data (Yuan et al., 2008). The experimental data were processed using GLITTER 4.0 (GEMOC) software.

GEOCHEMICAL FEATURES OF VOLCANIC ROCKS

Volcanic rocks occur as different-sized fragments in coarse-grained lithoclastic tuffs of the middle subformation of the Kupriyanovka Formation. The study of chemical composition of fragments of effusives and crystalloclastic tuff cement shows that they correspond to basalts, trachybasalts, and andesites. Rocks are characterized by low and moderate contents of K_2O and TiO_2 and are attributed to the calc-alkali series (Fig. 7a). Volcanics and tuffs of the Kupriyanovka Formation show differentiated REE distribution (Fig. 7b) with insignificant enrichment in LREE ($(La/Yb)_n$ = 4.3–7.7) in the absence of Eu anomaly (Eu/Eu* = 0.7–1.08). They are characteristic of depletion in highly charged elements (Nb, Ta, Ti, Zr) against the background of enrichment in large-ion lithophilic elements (Rb, Ba, Th, U), which is typical of suprasubduction complexes (Fig. 7c). As seen on the discrimination Zr/4–Nb×2–Y diagram, the composition points of volcanics and tuffs lie in the field of island arc basalts. This fact confirms the correctness of attributing these rocks to the island arc formations (Fig. 7d) (Meschide, 1986).

RESULTS OF GEOCHRONOLOGICAL STUDIES OF DETRITAL ZIRCONS

Detrital zircons were extracted from sandstones composing thin intercalations among Lower–Middle Ordovician carbonate rocks of the limestone–dolomite sequence. Sandstones are fine- to average-grained quartz rock varieties with carbonate–siliceous cement. Zircon, rutile, and tourmaline dominate among accessory minerals.

Sample Z-14108 (53°20′38.6″ N, 67°01′08.8″ E) was collected from sandstones of the section of the limestone–dolomite sequence (Figs. 3, 4, 6). In total, 141 zircon grains varying in color tint and size were extracted from this sample. The majority of zircon grains are less 50 μm in size; only 15 grains are ~100 μm. All zircon grains are well rounded and often fractured, contain inclusions, and in some zones are metamictized.

We performed U-Th-Pb study of 102 zircon grains, which yielded 108 concordant age values. The minimum concordant age obtained is 742 ± 4 Ma, and the maximum age is 2805 ± 20 Ma.

As seen on the probability density curve, concordant ages of detrital zircons from Sample Z-14108 are subdivided into four distinct groups: Late Mesoproterozoic group (age interval from 1027 ± 72 to 1193 ± 31 Ma; maximum ages of 1125 (dominant) and 1172 Ma); Early Mesoproterozoic group (age interval from 1227 ± 24 to 1569 ± 42 Ma; maximum ages of 1332 and 1453 Ma (dominant)); Late Paleoproterozoic group (age interval from 1602 ± 15 to 2019 ± 19 Ma with several maxima: 1682, 1745, 1816 (indistinct), and 1880 Ma (dominant)); Archean group (age interval from 2506 ± 14 to 2805 ± 20 Ma; maximum age of 2688 Ma). Among all ages, the age estimate of 1453 Ma dominates. In addition, there are single Neoproterozoic age datings in an age range of 742 ± 4–761 ± 6 Ma (Fig. 8a).

Sample Z-14115 (53°21′05.5″ N, 67°00′40.7″ E) was collected from sandstones of the upper part of the

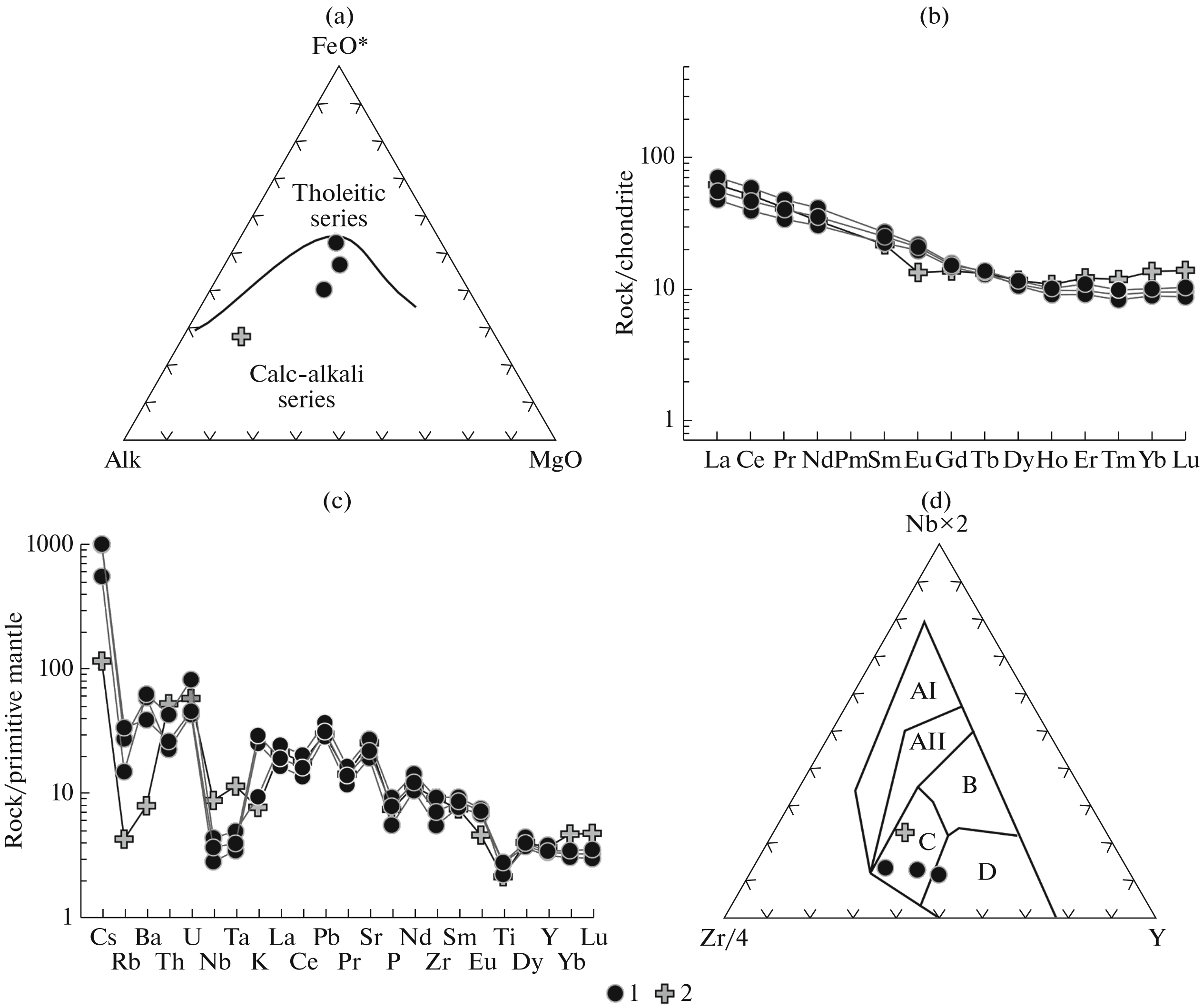


Fig. 7. (a) AFM diagram (Irvine et al., 1971), (b) chondrite-normalized REE distribution plots (Sun and McDonough, 1989), (c) primitive mantle-normalized multielement diagrams of trace elements (Sun and McDonough, 1989), (d) Zr/4—Nb×2—Y diagram for lithoclastic tuffs of the middle subformation of the Kupriyanovka Formation. (1) Rock fragments in lithoclastic tuffs, (2) cement of lithoclastic tuffs. Fig. 7d: AI, AII—fields of intraplate alkaline and tholeitic basalts, B—E-MORB basalts, D—N-MORB basalts, C—volcanic arc basalts (Meschide, 1986).

section of the limestone–dolomite sequence (Figs. 3 and 6). In total, 144 zircon grains of diverse color tints and size were extracted from the sample. The majority of grains are 50–80 μm in size and only some of them are ~100 μm. All zircon grains are well rounded. The U-Th-Pb analysis of 112 zircon grains yielded 87 concordant age values. The minimum concordant age is 807 ± 6 Ma, and the maximum age is 2811 ± 21 Ma.

As seen on the probability density curve, the concordant ages of detrital zircons from Sample Z-14115 are subdivided into distinct groups: Late Mesoproterozoic group (age interval from 1031 ± 27 to 1187 ± 35 Ma with two close maximum ages of 1085 and 1170 Ma (dominant)); Early Mesoproterozoic group (age interval from 1274 ± 39 to 1596 ± 22 Ma; maximum ages of 1394 and 1465 Ma); Late Paleoproterozoic group (age interval from 1613 ± 30 to 1876 ± 22 Ma; maximum ages of 1658, 1714, 1848 Ma (dominant)); Early Paleoproterozoic group (three age estimates with a narrow age range from 2473 ± 42 to 2483 ± 21 Ma; maximum age of ~2480 Ma); Archean group (age interval from 2631 ± 19 to 2811 ± 21 Ma; maximum age of 2745 Ma). Among all maximum ages, 1465 and 1848 Ma are the most significant. In addition, there are single Neoproterozoic (807 ± 6 Ma) and Early Paleoproterozoic (1972 ± 65 and 2146 ± 16 Ma) age estimates (Fig. 8b).

Integrated consideration of geochronological study results of detrital zircons from Samples Z-14115 and Z-14108. All zircons (227 grains in total) extracted and studied are well rounded and 50–80 μm in size (less commonly 100 μm or more). In total, 195 age estimates with an appropriate degree of discordance were obtained.

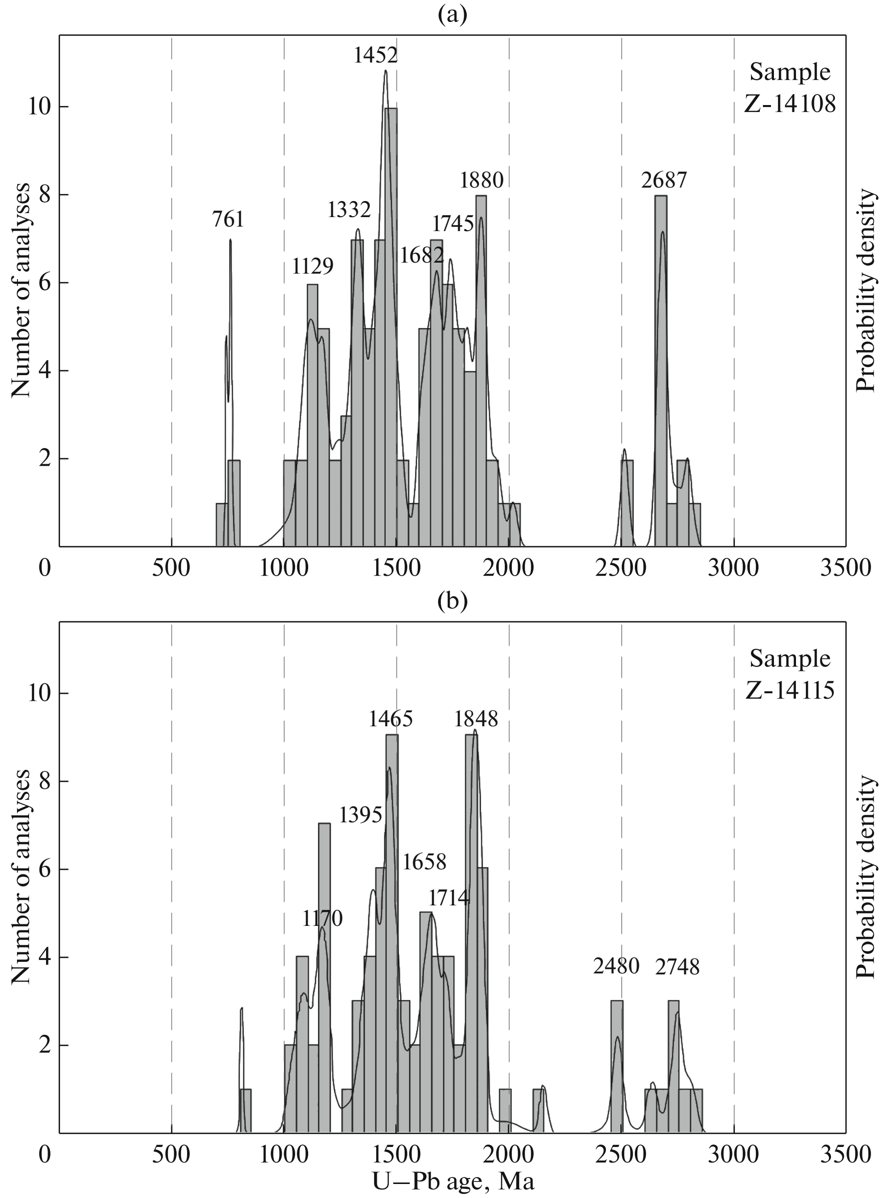


Fig. 8. Age histograms and probability density distributions of detrital zircons from sandstones of the limestone–dolomite sequence. (a) Lower unit (Sample Z-14108), (b) upper unit (Sample Z-14115).

Visual comparison of age histograms and probability density curves complied for both samples shows strong resemblance of them. Age boundaries of Mesoproterozoic, Paleoproterozoic, and Archean groups and proportions of zircon groups are very similar. There are insignificant differences only in age estimates obtained for single zircons and maximum age estimates. The quantitative correlation of the geochronological data obtained for two samples using the Overlap–Similarity Program software (Gehrels, 2012) has confirmed this fact: degree of similarity of age datasets of detrital zircons from Lower–Middle Ordovician sandstones sampled in different parts of the section of the limestone–dolomite sequence is 0.866, and the overlap is 0.863.

Concordant age values of the total set of detrital zircons from the two samples cover an age interval from 742 ± 4 ($D = 6.5\%$) to 2811 ± 21 Ma ($D = 5.8\%$).

Among them are 4 Neoproterozoic, 95 Mesoproterozoic (48.7% of all ages obtained), 75 Paleoproterozoic (38.5%), and 21 Archean (10.8%) age estimates.

The Neoproterozoic age datings yield three close age maxima on the probability density curve: 743, 761 (dominant), and 809 Ma. The group of Late Mesoproterozoic age datings covers an interval from 1027 ± 72 to 1236 ± 21 Ma with a maximum of 1168 Ma. The group of Early Mesoproterozoic age datings is in the interval from 1262 ± 20 to 1569 ± 42 Ma with maxima of 1460 (dominant) and 1345 Ma. The Late Paleoproterozoic group covers an age interval from 1592 ± 22 to

1972 ± 65 Ma with age maxima of 1668 and 1863 Ma (dominant). The most ancient Paleoproterozoic group includes three age datings varying in a narrow range from 2473 ± 42 to 2483 ± 21 Ma, which together with Late Archean age datings yield a peak of ~2514 Ma. Other Archean age datings form a compact group with an age range from 2631 ± 19 to 2811 ± 21 Ma and a distinct maximum of 2693 Ma (Fig. 9a).

Possible source areas of detrital zircons. As evidenced from the U-Pb geochronological studies, all detrital zircons from sandstones of the limestone–dolomite sequence yield Precambrian age. Taking into account the structural position of the Ordovician strata of the Mariev Zone, provenance areas of Precambrian zircons could be located only eastward, within the Kokchetav massif. Here, there are widespread Upper Precambrian quartzite–schist sequences (Kokchetav Division), which are characterized by the occurrence of horizons and lenses of zircon–rutile concentrate, representing paleoplacers, in quartzites (Danilov and Pankratova, 1965). In recent years, zircons from these placers were studied (Degtyarev et al., 2015; Kovach et al., 2017). It was established that concordant ages of detrital zircons from three zircon–rutile ore occurrences of the Kokchetav massif are predominantly in the following age intervals: 1017–1528, 1628–1946, and 2653–2739 Ma with age peaks of 1116 (n = 19), 1245 (n = 27), 1332 (n = 26), 1380 (n = 21), 1469 (n = 40), 1648 (n = 11), 1709 (n = 9), 1776 (n = 5), 1856 (n = 6), 1921 (n = 9), and 2703 (n = 6) Ma. Single zircon grains have Early Proterozoic (1968–2331 Ma) and Neoarchean (2547–2597 and 2816–2841 Ma) concordant ages. Accordingly, the main provenance areas supplying the terrigenous material for quartzite–schist sequences were of Mesoproterozoic age; Paleoproterozoic and Neoarchean sources played a smaller role (Degtyarev et al., 2015).

We compared the results of study of detrital zircons from quartzite–schist strata of the Kokchetav massif and the limestone–dolomite sequence of the Mariev Zone using the Overlap–Similarity Program software. Deposits of the quartzite–schist strata of the Kokchetav massif have no detrital zircons with ages in a range of 800–760 Ma, which were found in Ordovician sandstones of the Mariev Zone. This is in good agreement with the Early Neoproterozoic age of quartzite–schist sequences. Because of this, Late Neoproterozoic age datings were not taken into consideration in the correlation. As a result, it was established that the similarity of age datasets for detrital zircons older than 1000 Ma from sandstones of different parts of the section of the Lower–Middle Ordovician limestone–dolomite sequence of the Mariev Zone and the total dataset of detrital zircons from the quartzite–schist sequences of the Kokchetav massif is 0.849, and the overlap of age datasets is 0.871 (Fig. 9b).

Thus, the Early Neoproterozoic quartzite–shale sequences of the Kokchetav massif are the most likely provenance area at the formation of the limestone–dolomite sequence of the Mariev Zone.

EVOLUTION OF SEDIMENTATION ENVIRONMENTS

The nearly complete section of the Mariev Zone comprises sequences of a wide stratigraphic interval from Tremadocian Stage of the Lower Ordovician to the lower Sandbian Stage of the Upper Ordovician. The structural features of the section and the rock composition allow us to suggest that throughout this time interval the sedimentation environment changed from closed lagoons to a relatively deep marine basin with normal salinity and active circulation of water masses (Fig. 10). In this case, throughout the sedimentation period, there existed a sufficiently high level of terrigenous material washout that resulted in the deposition of thick strata.

The lower part of the limestone–dolomite sequence is composed of dolomite–siltstone deposits and is characterized by occurrence of stromatolites and sedimentary breccias with distinct landslide structure, which contain fragments of carbonate rocks in clayey–carbonate cement. There are synsedimentation cracks, filled with brecciaed material. In this part of the section, there is no distinct bedding, which can be due to a quite high rate of sedimentation at a significant role of suspension flows, talus, and landslides. The high rate of sedimentation and uneven character of sedimentation indicate suppression of stromatolite structures and almost complete absence of ichnofossils and fossil remains. Such sedimentation environments are characteristic of shallow lagoons and bays, protected from the impact of currents and waves.

High rates of sedimentation were preserved at the formation of the upper—siltstone–dolomite—part of the limestone–dolomite sequence. The latter is characterized by an increase in the proportion of the terrigenous fraction at sporadic occurrence of interlayers of gray limestones. Limestones contain rare algal remains, inarticulate brachiopods, and single conodont elements. There are thinly laminated deposits of the mixed siltstone–dolomite composition with insignificant predominance of either carbonate or terrigenous components and their frequent alternation. The thickness of individual intercalations of dolomite and siltstones varies from a few millimeters to several centimeters. Contacts between beds are gradual, less commonly sharp, which is characteristic of aleuropelitic sediments of the shallow coastal zone. Only the upper part of the limestone–dolomite sequence is composed of thick units of thinly laminated brownish red, reddish yellow, and orange siltstones. The lower content of the dolomite fraction and periodic formation of pure limestones in the upper part of the limestone–dolomite sequence indicate deeper and seaward sedimentation environments of this part of the section.

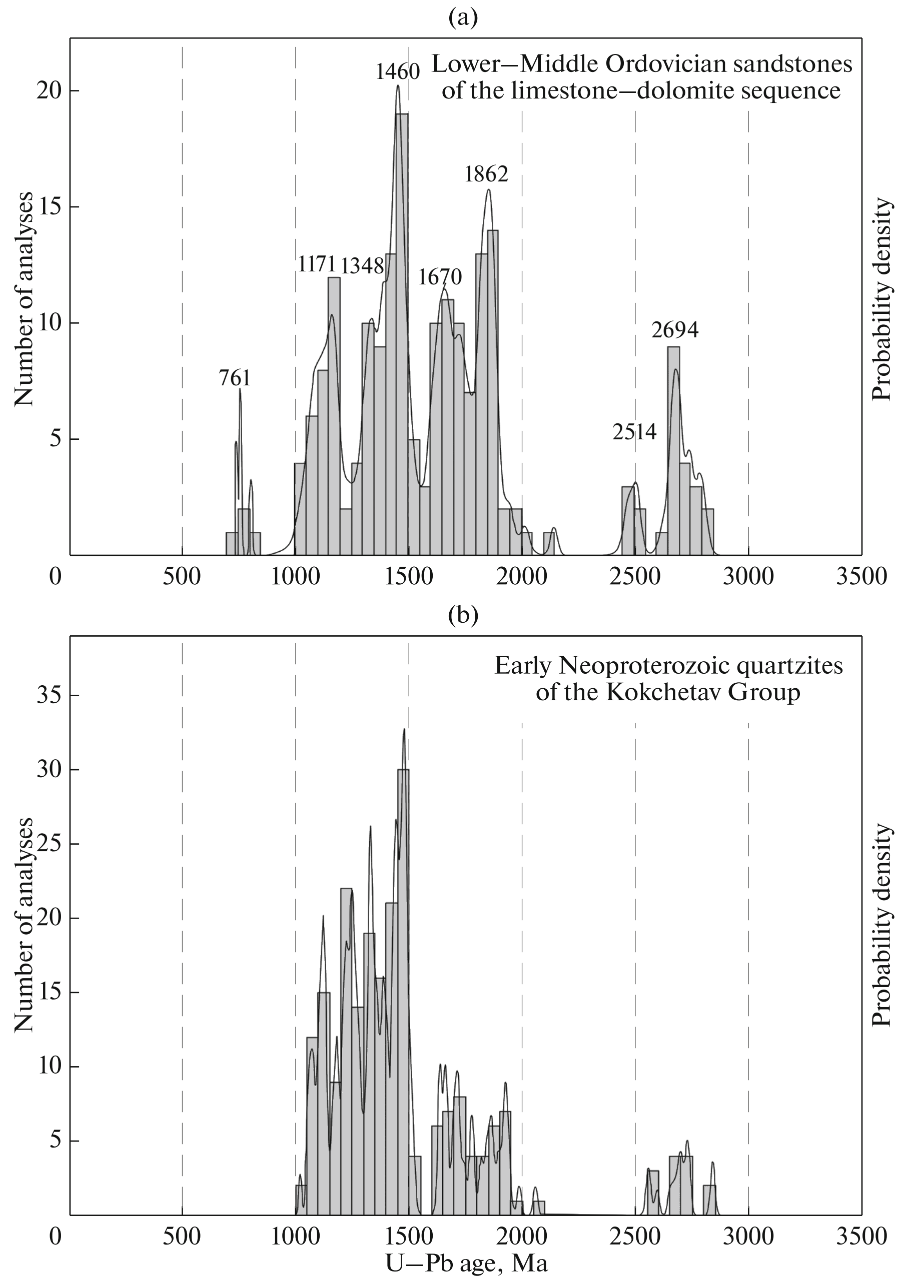


Fig. 9. Age histograms and probability density distributions of detrital zircons. (a) Lower–Middle Ordovician sandstones of the limestone–dolomite sequence (Samples Z-14108 and Z-14115), (b) Early Neoproterozoic quartzites of the Kokchetav Division (Degtyarev et al., 2015; Kovach et al., 2017).

The upper part of the limestone–dolomite sequence is crowned by a thick bed of clayey limestone with stromatolitic structures, as well as with ripple marks and mud cracks on bedding planes of carbonate beds, which marks a fall in sea level.

Beginning from the onset of the deposition of the Kupriyanovka Formation, the character of sedimentation changed. The fine-grained terrigenous unit of the lower subformation has primary gray color, caused by occurrence of organic carbon. A higher content of organic carbon is characteristic of deposits formed as a result of erosion of carbon-rich coastal shallow deposits. The development of intense erosion of shallow-water strata is confirmed by the occurrence of blocks of oncolitic limestones at the base of the Kupriyanovka Formation section. The lower dark fine-grained terrigenous unit is followed upsection by irregular alternation of reddish brown to greenish mudstones, siltstones, and fine- and coarse-grained arenaceous sandstones. In general, the bedding is horizontal; sometimes, rhythmical alteration of mudstones and siltstones with thin sandstone intercalations is

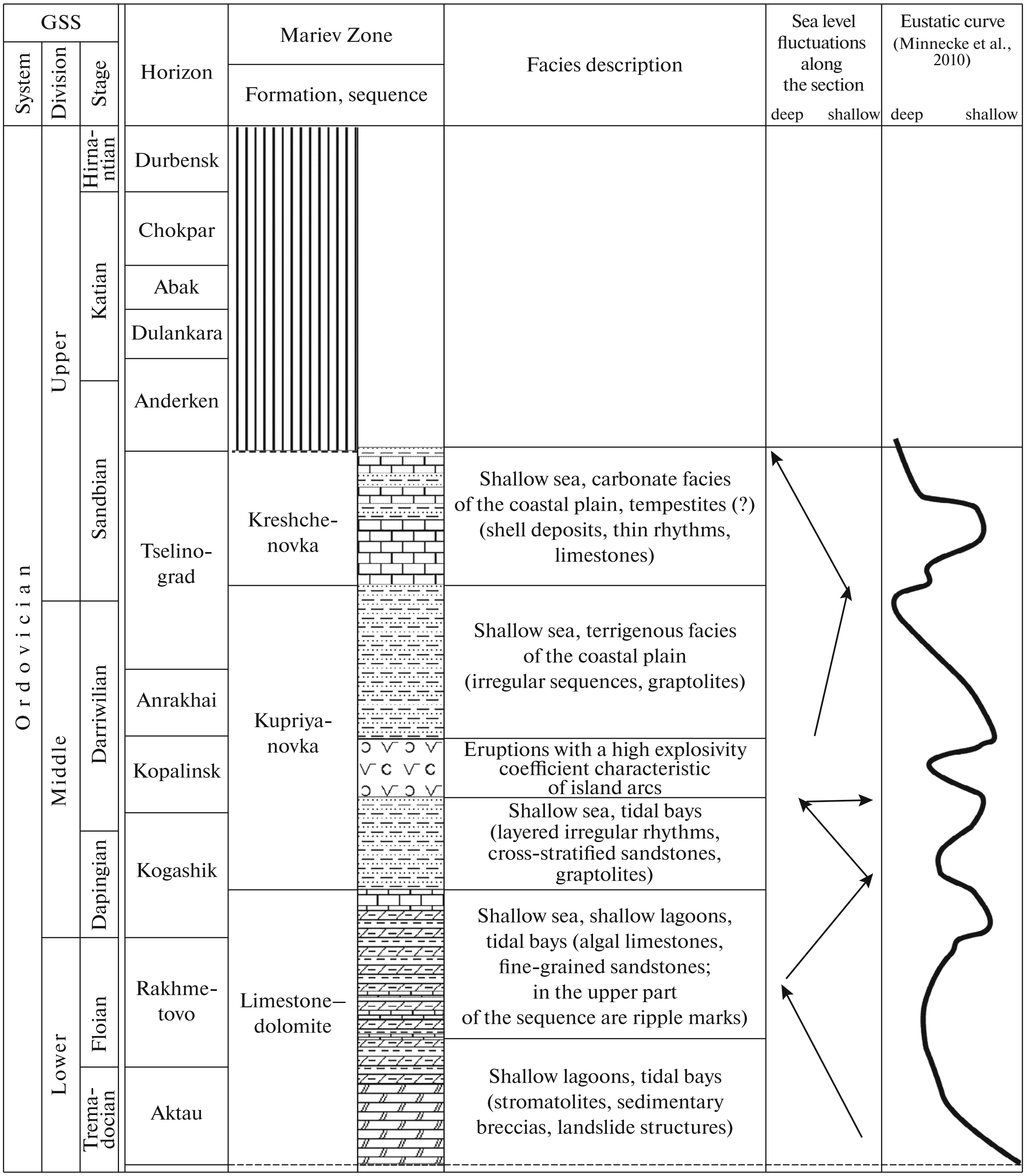


Fig. 10. Evolution of the formation settings of the Ordovician sequences of the Mariev Zone. GSS—general stratigraphic scale, Hirn.—Hirnantian.

observed. The absence of graded bedding indicates relatively shallow sedimentation environments of this unit, deeper than sedimentation environments of the underlying deposits. In the upper part of the lower subformation are cross-stratified sandstones, which deposited in the shallow water environment of tidal bays under conditions close to subaerial.

During accumulation of the middle subformation of the Kupriyanovka Formation, which is composed of monotonous nonlaminated coarse-grained lithoclastic tuffs of mafic and intermediate to mafic composition, volcanic eruptions with a high explosivity index characteristic of the island arc complexes play an important role.

The upper subformation of the Kupriyanovka Formation is composed of monotonous greenish and gray siltstones and fine-grained sandstones, which are characterized by indistinct bedding and an absence of rhythmicity. Apart from rare fossil remains (single finds of graptolites), these features indicate a high rate of sedimentation under the conditions of a relatively deep water basin.

The transition to the Kreshchenovka Formation is marked by the increase in rock carbonate content. The section of this formation was previously interpreted as carbonate–clayey flysch, composed of pelitomorphic and organogenic limestones, calcareous siltstones and mudstones (*Geologiya*..., 1987). However, our observations show that there is no distinct rhythmicity in the complete section of the sequence, and some units are characterized by lithological and lateral heterogeneity. The graded bedding was identified only in layered organogenic limestones of the lower part of the formation, which has pronounced flyschoid, probably tempestite, character. Mass accumulations of brachiopods redeposited at some stratigraphic levels of the lower part of the Kreshchenovka Formation are evidence of local development of barrier facies.

Thus, within the northwestern frame of the Kokchetav massif, there was a general trend toward the deepening of sedimentation environments from the Early to Late Ordovician with periodic sea level rises in the Dapingian and Early Darriwilian ages (Fig. 10). This change in sedimentation environments is not correlated with a curve of eustatic movements in the Ordovician (Munnecke et al., 2010) and indicates the participation of tectonic processes.

CONCLUSIONS

The comprehensive study of sedimentary and volcanogenic-sedimentary sequences including the detailed mapping of reference sites, the study of structural features of the sequences, and paleontological and geochemical studies, as well as dating of detrital zircons, made it possible to obtain a large volume of principally new data and to contribute significant changes to existing stratigraphic scales and models of tectonic evolution.

On the basis of conodonts, the most ancient limestone–dolomite sequence, ascribed previously to the Cambrian, has Early to Middle Ordovician age. The overlying tuffaceous–terrigenous Kupriyanovka Formation is attributed to the Middle Ordovician. The compositional features of average to basic tiffs composing the middle subformation of this formation indicate their formation in suprasubduction settings within the island arc zone. On the basis of conodonts, the lower part of the section of the terrigenous–carbonate Kreshchenovka Formation, which crowns the sequence of the Mariev Zone, is attributed to the lower part of the Sandbian Stage of the Upper Ordovician.

The study of detrital zircons from Lower–Middle Ordovician terrigenous rocks of the limestone–dolomite sequence demonstrates that the main provenance area at the accumulation of this sequence was Early Neoproterozoic quartzite–schist deposits of the Kokchetav massif.

The character of the section and lithological features of sedimentary rocks indicate variations in sedimentation conditions within the Mariev paleobasin during the Ordovician. During this period of time, the sedimentation environments changed from closed lagoons to a relatively deep-water sea basin with normal salinity and active circulation of water masses. The formation of the tuffaceous–terrigenous Kupriyanovka Formation with a large thickness allows us to assume that the erosion of provenance areas and accordingly transport of the terrigenous material in the Middle Ordovician occurred at a high level. A general trend toward the deepening of sedimentation environments from the Early to Late Ordovician was interrupted by sea level rises in the Dapingian and early Darriwilian ages.

Owing to the comparison of the Ordovician complexes of the Mariev, Sterlitamak, and Imanburluk zones, composing the western and northwestern frames of the Kokchetav massif, we have established that these zones are substantially different and were formed in different geodynamic settings.

New data on the geochronology of stratified sequences of the Mariev Zone can be used in compilation of a new regional stratigraphic scale of Kazakhstan.

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